Design of SPOKE Type BLDC Motor for Traction Application Considering Irreversible Demagnetization of Permanent Magnet

Jin Hur* and Gyu-Hong Kang †

Abstract - This paper presents a design strategy of SPOKE type BLDC motors considering an irreversible demagnetization of a permanent magnet (PM). So the irreversible demagnetization characteristic of the motor is analyzed by rotor structure. The instantaneous currents in either starting or lock rotor condition, which are calculated from the current dynamic analysis, are applied to the analysis of the irreversible demagnetization field by FEM. In irreversible demagnetization analysis by FEM, the variation of residual flux density in PM is analyzed using the non-linearity of magnetic core on B-H plan. The analysis results are compared to several rotor structures and used for optimize the rotor structure.

Keywords: Spoke type BLDC motor, Traction, Irreversible Demagnetization, Dynamic analysis, flux barrier, high torque.

1. Introduction

PM motors have been interested as a good choice for many types of applications. There is a continuing need for new motors with reduced size and higher performance [1]. A SPOKE type BLDC motor is to have a rotor structure of interior type PM with higher saliency ratios. This means the magnetic flux generated by the PM's arrangement of the SPOKE type BLDC motor is highly concentrated in the air gap as shown in Fig. 1 and the magnetic flux generated by the PMs becomes concentrated, resulting in the increase of higher torque density per volume. The reluctance torque induces torque ripple and vibration in the motor and surrounding structures. However, it could be contributed to from the effective torque by current control in the inverter fed system [2], [3]. Therefore, the PM arrangement and driving control circuit have to be considered together in the design stage of the SPOKE type BLDC motor.

In the PM motor, the instantaneous current in the starting or locked rotor condition could cause the tremendous external demagnetizing field for the PMs. It is occurring the irreversible demagnetization and is reducing the residual flux density of the PM. So, it is cause the deterioration of the performance of PM type BLDC motor. Therefore, the irreversible demagnetizing characteristics of the PM must be considered for designing the rotor structure of BLDC motor.

The main object of this paper is to design shape high performance SPOKE type BLDC motors considering the irreversible demagnetization of PMs through a transient analysis including driving circuit. So, in this paper, we compared the irreversible demagnetization characteristics of the SPOKE type BLDC motor with an interior type PM motor (IPM) and surface mounted PM motor (SPM), and confirmed that the SPOKE type motor has a great advantage over the SPM and other IPMs toward the trend of high torque and small size. From the results, the design parameters such as PM positions and structure etc. due to irreversible demagnetizing effects are investigated and applied on the design of the SPOKE type BLDC motor.

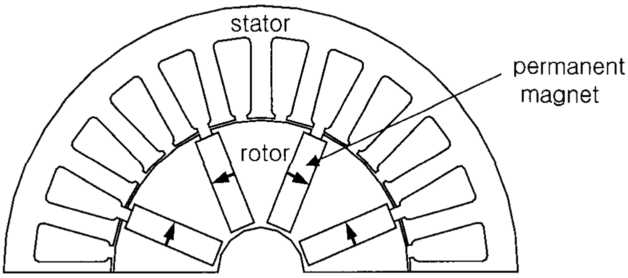

Fig. 1 Geometry of a SPOKE type BLDC motor.

2. Analysis

2.1 Current Dynamic Analysis

In the SPOKE type PM motor, the reluctance torque strongly influences the torque characteristics. In addition, the reluctance torque by difference of d-q axis inductances is induced torque ripple and vibration of machine having two times of periods of electromagnetic torque [1], [2].

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Received April 13, 2004 ; Accepted March 8, 2005

However, it could be contributed on the effective torque by control of the current phase in the inverter fed system. So, the driving circuit considering the conduction and freewheeling period must be considered to exactly analyze the characteristics and determine the optimal current phase for high performance.

This paper develops a dynamic analysis method for obtaining optimal current phase. This method coupled magnetic field by FEM with electric circuit considering controlled current phase angle in the voltage source inverter. The spatial distribution of circuit parameters such as the back EMF, as well as self and mutual inductances are calculated using the developed method, and then they there are applied to electric circuit analysis for the instantaneous current and torque controlled by current phase with advanced angle [3].

Fig. 2 shows the analysis process of instantaneous torque and Fig. 3 shows the current flow in the conduction and freewheeling period occurring at the six-switched converter.

In the conduction period, two phases out of three phases are energized as shown by the solid line in Fig. 3(a). The voltage equation for computation of the instantaneous current in the conduction period is given by

$$V_a - V_b = R(i_a - i_b) + \frac{d}{dt}\left(L_a(\theta) - M(\theta)\right)i_a + e_a - \frac{d}{dt}\left(L_b(\theta) - M(\theta)\right)i_b + e_b \quad (1)$$

$$\frac{di_a}{dt} = \frac{V_a - V_b - e_a - e_b - 2Ri_a}{L_a(\theta) + L_b(\theta) - 2M(\theta)} \quad (2)$$

However, when the phase commutates from C to B, A-B phases are conducted immediately after switching off the A-C phases and C phase current is freewheeling through diode D_2. The current freewheeling in the commutation period is generated by inductance of the motor. So, the voltage equation should be reconstructed to three phases considering the freewheeling current as follows:

$$\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \end{bmatrix} = -\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} R/(L_a(\theta)-M(\theta)) \\ R/(L_b(\theta)-M(\theta)) \end{bmatrix}\begin{bmatrix} i_a \\ i_b \end{bmatrix} + \begin{bmatrix} 1/3 & 0 \\ 0 & 1/3 \end{bmatrix}\begin{bmatrix} R/(L_a(\theta)-M(\theta)) \\ R/(L_b(\theta)-M(\theta)) \end{bmatrix}\begin{bmatrix} 2V_{ac} - V_{bc} - 2e_a + e_b + e_c \\ 2V_{bc} - V_{ac} + e_a - 2e_b + e_c \end{bmatrix} \quad (3)$$

The instantaneous peak current in starting or transient state is generated to irreversible demagnetization of the PM. Fig. 4 shows the demagnetization curve of a ferrite type permanent magnet on a B-H plane. When operating point P_1 moves to P_2 due to the external demagnetizing field, the residual flux density, B_r, is decreased to B_r`, and the irreversible demagnetization is occurred.

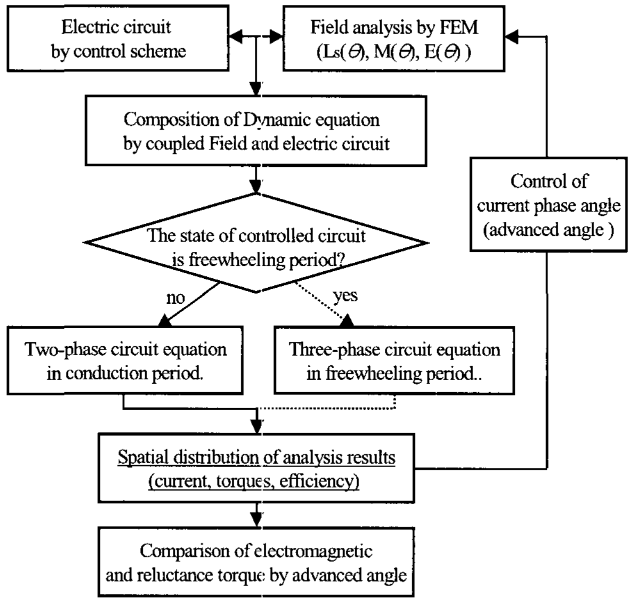
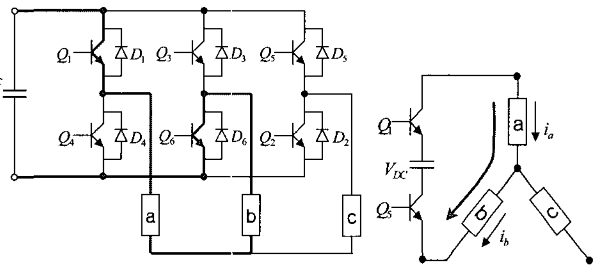
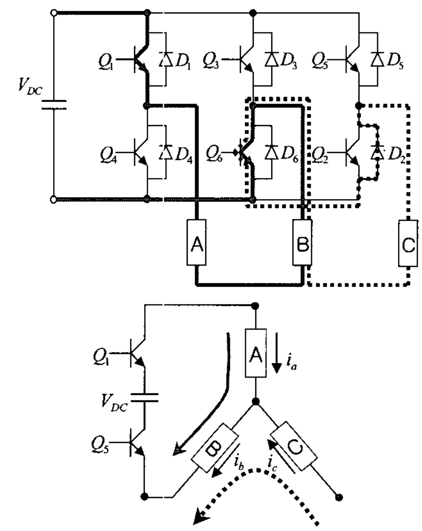


Fig. 2 Schematic diagram for Dynamic analysis process by coupled field and electric circuit.



(a) Current flow in conduction period



(b) Current flow in freewheeling period

Fig. 3 Current flow in conduction and freewheeling period of BLDCM

2.2 Method of Irreversible Demagnetization Analysis

The peak current at starting or during transient state, which is obtained from the simulation results in Fig. 5(b), is calculated using current dynamics analysis and the calculated peak current is used for the irreversible demagnetizing FE analysis for external magnetic field computation [4].

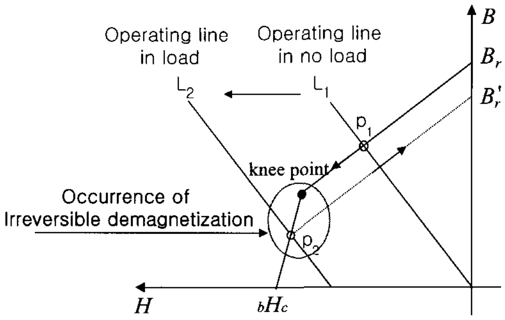
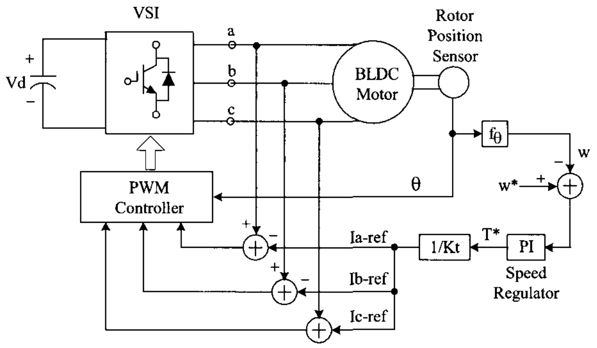
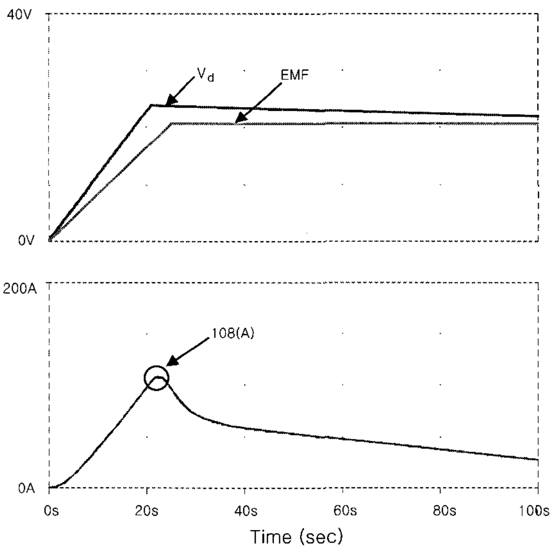


Fig. 4 Demagnetization curve of a ferrite type PM on a B-H plane.



(a) Speed and torque control loop.



(b) Voltage and current waveforms (upper: DC-Link voltage and back EMF; lower: Instantaneous current).

Fig. 5 Characteristics of Instantaneous current in PMs.

Fig. 6 presents the process of irreversible demagnetization analysis of BLDC motors. As the magnetic flux density in each element of the permanent magnet region is less than the knee point by the external demagnetizing field the residual flux density of the element renews in analysis process.

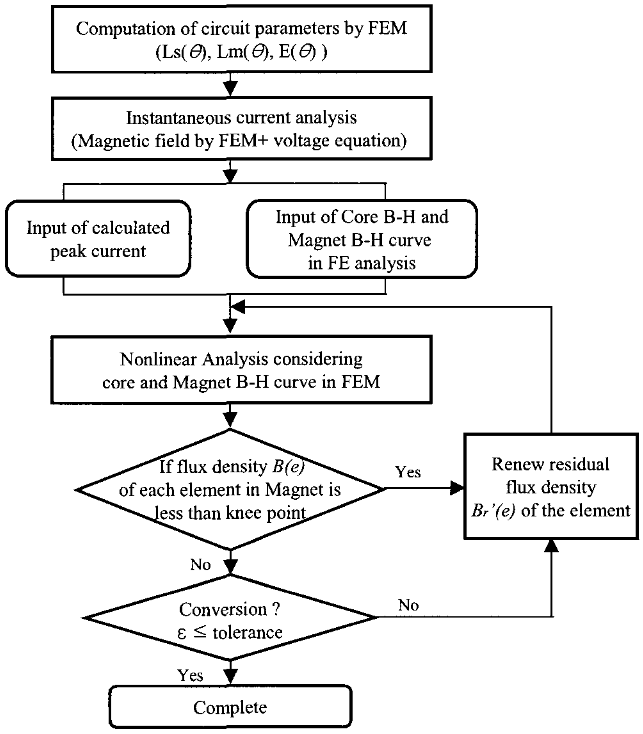


Fig. 6 Irreversible demagnetization analysis process of PM type BLDC motors.

3. Results and Discussion

The steady state characteristics and irreversible demagnetization phenomena of the SPOKE type BLDC motor are calculated by proposed FEM and the results are compared with the SPM BLDC motor.

Fig. 7 shows the inductances distribution by the rotor positions. In case of the SPM type BLDC motor, the inductances are constant on rotor positions and otherwise the inductances of the SPOKE type BLDC motors are varied by the rotor positions and they are larger than inductances of the SPM type BLDC motor, which results from the reduced reluctance. Therefore, the SPOKE type BLDC motor generates the reluctance torque due to the variation of inductances with the rotor position in addition.

In the SPOKE type BLDC motor, PMs are arranged to both sides of the rotor pole face and it leads to concentrate the magnetic flux generated by the PMs in the air gap. Therefore, the back EMF and the torque of the SPOKE type BLDC motor are larger than the other type motors.

The compared results of commutation torque according to the rotor structures are shown in Fig. 8. From these results, it is noted that the torque of the SPOKE type BLDC motor is higher than that of the SPM type BLDC motors.

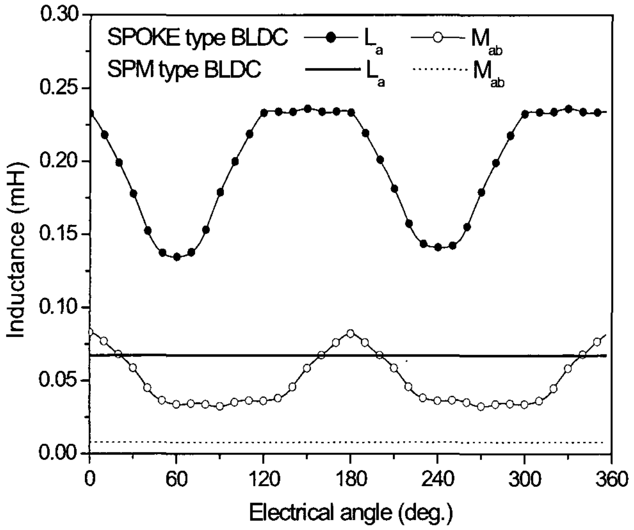


Fig. 7 Inductances by the rotor positions.

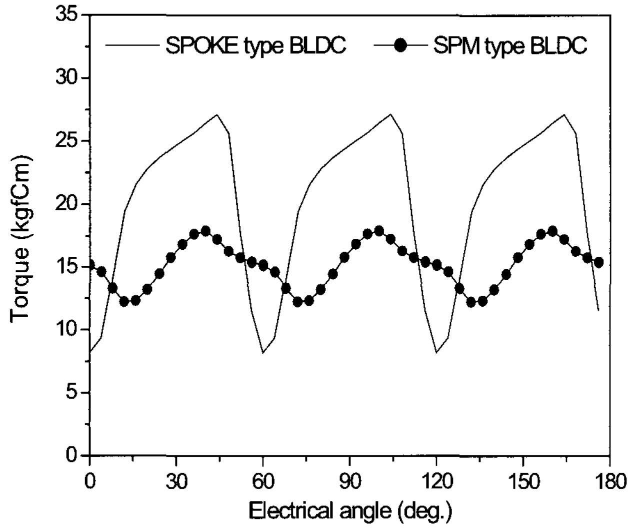
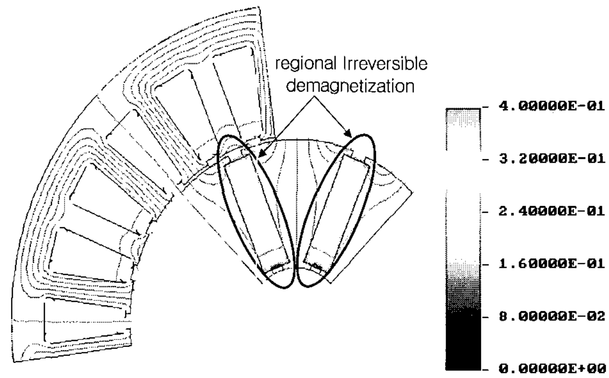
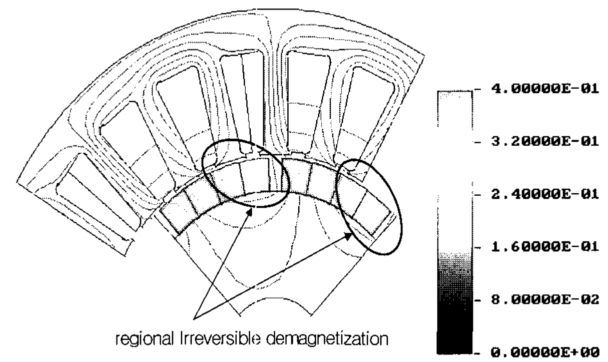


Fig. 8 Characteristics of commutation torques with the rotor structures.

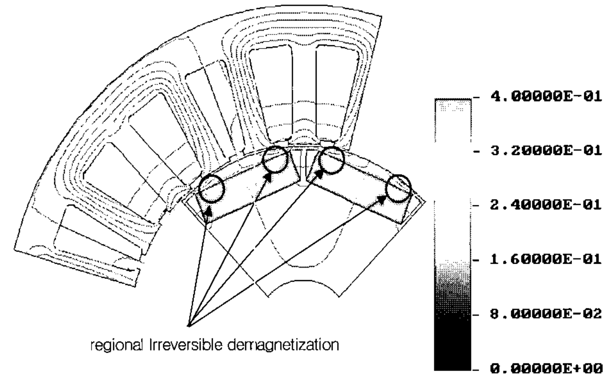
From the irreversible demagnetization analysis, the results of residual flux density variation in PMs are compared to several types of rotor structures. Fig. 9 shows the variation of residual flux density comparison of each rotor structure in the PM by (-) *d*-axis instantaneous peak current. In case of the SPOKE type rotor, the PM is demagnetized entirely by the external field on the other hand the SPM type rotor occurred partial irreversible demagnetization. Moreover, the IPM type rotor is hardly demagnetized so the regional irreversible demagnetization rate according to rotor structure is different.



(a) SPOKE type BLDC motor



(b) SPM type BLDC motor

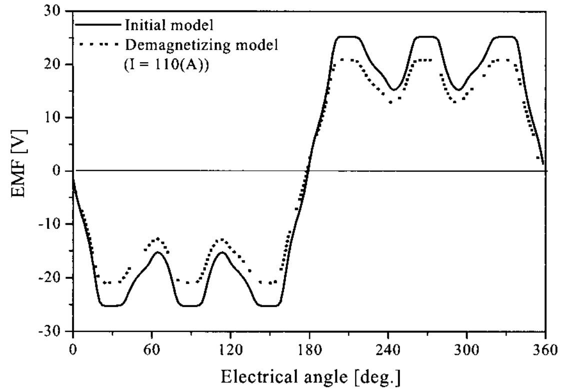


(c) IPM type BLDC motor

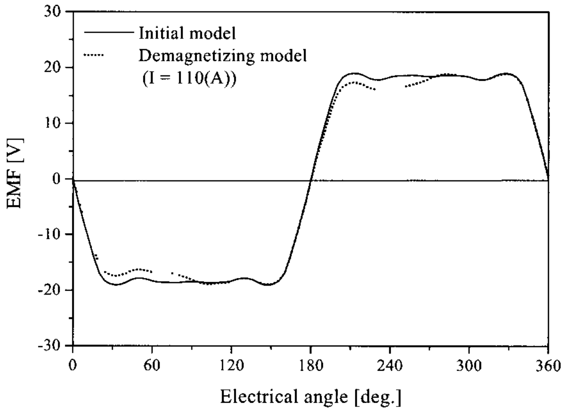
Fig. 9 Comparison of residual flux density

Fig. 10 shows the back EMF distribution between initial conditions that the PMs are fully magnetized, and the demagnetized condition that is induced in the external field on the (-) *d* axis. The air gap flux of the SPOKE type BLDC motor is concentrated so that the back EMF is largest in three types of rotors on the other hand it has weak external demagnetizing effect. The IPM type BLDC motor has robust demagnetizing field but the back EMF is less then the other type rotor.

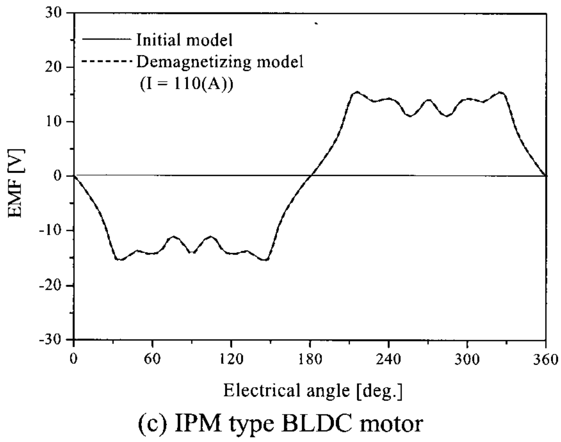
Therefore, the design of the SPOKE type BLDC motor should be considered in relation to air gap flux density and irreversible demagnetization effect by rotor structure.



(a) SPOKE type BLDC motor



(b) SPM type BLDC motor



(c) IPM type BLDC motor

Fig. 10 Back EMF characteristics of initial versus demagnetizing model

4. Design of Spoke type BLDC Motor

4.1 Consideration of design parameters

In the SPOKE type BLDC motor, PMs are arranged to both sides of the rotor pole face, so it is lead to concentrate the magnetic flux generated by PMs in the air gap. Therefore, for the higher performance of the SPOKE type BLDC motor, we should fully investigate the distribution characteristics of magnetic flux according to the design parameters.

In this paper, the pole number and PM height versus arc length of the pole face is chosen to design parameters under the condition having a constant rotor dimension as shown in Fig. 11.

Fig. 12 shows an air gap flux density distribution according to the pole numbers. From the effect of flux concentration, the magnetic flux density in the air gap increases with pole number until 0.5[T] in spite of the residual flux density of 0.39[T]. The characteristic of magnetic flux density due to pole shape ratio (k), which is PM height versus arc length of pole face, is shown in Fig. 12. As shown in Fig. 12, the magnetic flux density have a large variation according to the pole shape ratio, so it is a very important design parameter for high performance design of the SPOKE type BLDC motor.

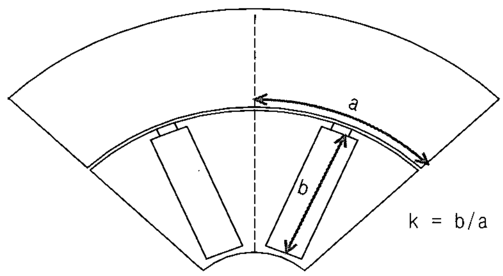


Fig. 11 Design parameter by PM height versus arc length of pole face (k)

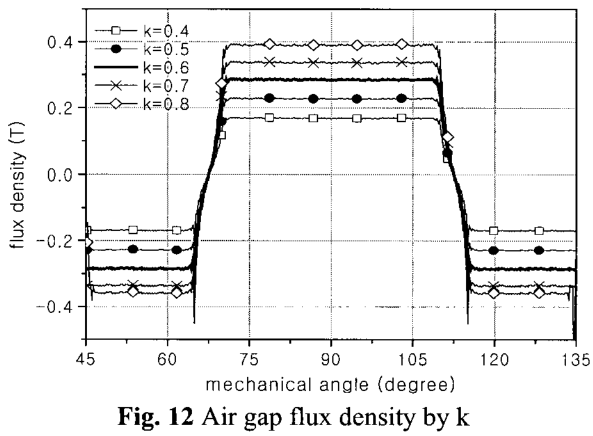


Fig. 12 Air gap flux density by k

4.2 Consideration of design parameters

The design results are presented to Table I compared with design result of SPM type BLDC motor. As shown in Table I, the rotor diameter of the SPOKE type BLDC motor is less than the SPM type BLDC motor and the rotor volume is reduced by about 25(%) under constant power condition. Moreover, the magnet volume is reduced by about 19(%) in comparison with the SPM type BLDC motor. Also, the energy density of the SPOKE type PM motor is higher then the SPM type BLDC motor.

From the results, the design of the SPOKE type BLDC motor has to consider the irreversible demagnetization characteristics of the PM because of the concentration of the magnetic flux.

Table 1 DESIGN RESULTS BY EQUIVALENT MAGNETIC CIRCUITS

Items	SPM type BLDC	SPOKE type BLDC
Output power [W]/RPM	300 / 3000	300 / 3000
Pole #/ Slot #/ Turn #	8 / 24 / 64	8 / 24 / 64
Teeth width (mm)/ Slot depth (mm)	**1.94 / 8.2**	**2.3 / 8.7**
Stack length / Rotor diameter (mm)	61.1 / 61.1	55.5 / 55. 5
Magnetization Length of PM (mm)	2.9	2.9
Width of PM (mm)	18.7	16.7
Total volume of PM (Cm^3)	**26.5**	**21.5**
Rotor volume (Cm^3)	**179.15**	**134.27**

5. Shape Design for Irreversible Demagnetization

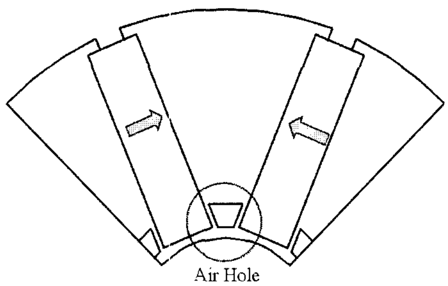
From the analysis results, it is noted that SPOKE type BLDC motors have a great advantage on high energy density and torque per volume in comparison with SPM type BLDC motors. On the other side, the irreversible demagnetizing effect becomes very serious by external demagnetizing field. Therefore, in order to design PM type BLDC motors, the characteristic analysis as well as the irreversible demagnetizing analysis according to rotor structure should be considered. Moreover, leakage flux is generated between magnets because PMs are inserted in the rotor. Therefore, if this leakage flux can be minimized, the torque and output power density can be much more increased.

In this paper, a rotor shape design has been performed in order to minimize the leakage flux component and increase torque density. As design variables, air holes and flux barriers for reducing leakage fluxes are constructed between PMs and the proposed rotor shape and flux distribution are depicted in Figs. 13 and 14, compared with the reference model in Fig. 1.

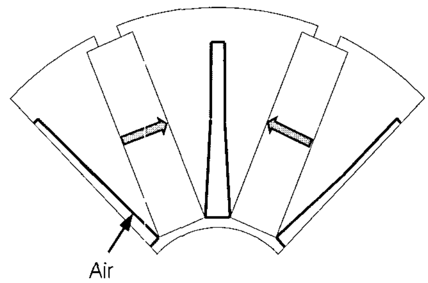
From the analysis results, most fluxes are inclined into the stator, which is due to increased magnetic resistance and reduced leakages. It means that the air-gap flux density becomes increased and as the result of that the output torque is also increased. Fig. 15 shows the torque characteristics and comparison of two types of proposed SPOKE type BLDC motors, which are air hole type rotor and flux barrier type rotor compared with the torque of the SPM type BLDC. From the results, the flux barrier type motor has superiority over the other types of motors in the torque point of view. Therefore, in the case of the SPOKE type BLDC motor, if the rotor shape can be modified in order to much more concentrate of rotor flux, the torque one can dramatically increase.

In the shape design of the PM type BLDC motor, the irreversible demagnetization characteristic is as important as the maximization of torque and efficiency. Therefore, the irreversible demagnetizing analysis of the proposed barrier type SPOKE type BLDC motor is carried out.

Fig. 16 shows the back EMF distribution between the initial condition of the reference model, on which PMs are fully magnetized, and the demagnetized condition, which is induced by the external demagnetizing field on the (-)d axis in the reference model and the proposed barrier type model. The back EMF of the reference model by the external demagnetizing field is reduced about 18(%), which is from 19.2(V) to 15.6(V) on the other hand the back EMF of the flux barrier type SPOKE type BLDC motor is reduced about 5.3(%) by 19.2(V) to 17.9(V). Therefore, the reference model indicates fragile characteristics from the external demagnetizing field and on the other hand, the proposed barrier type SPOKE type BLDC motor is robust to the demagnetizing field.

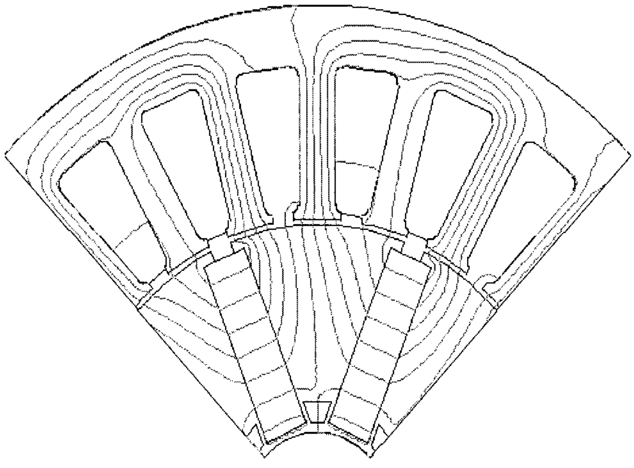


(a) Air-hole type SPOKE rotor

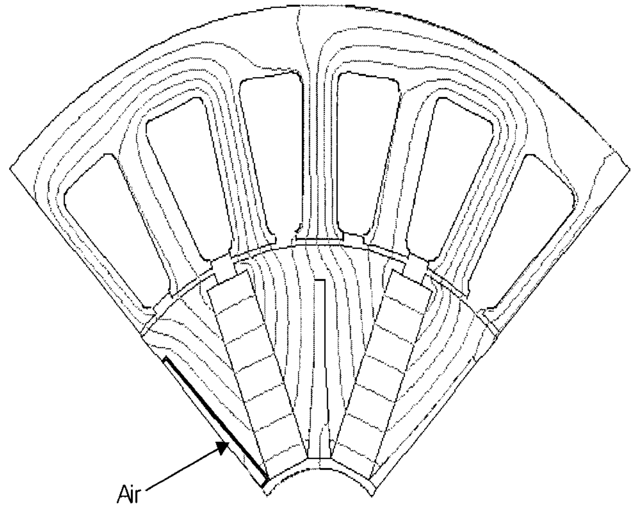


(b) Flux barrier type SPOKE rotor

Fig. 13 Rotor structure of proposed model.



(a) Air-hole type SPOKE rotor



(b) Flux barrier type SPOKE rotor

Fig. 14 Equipotentional distribution of proposed model.

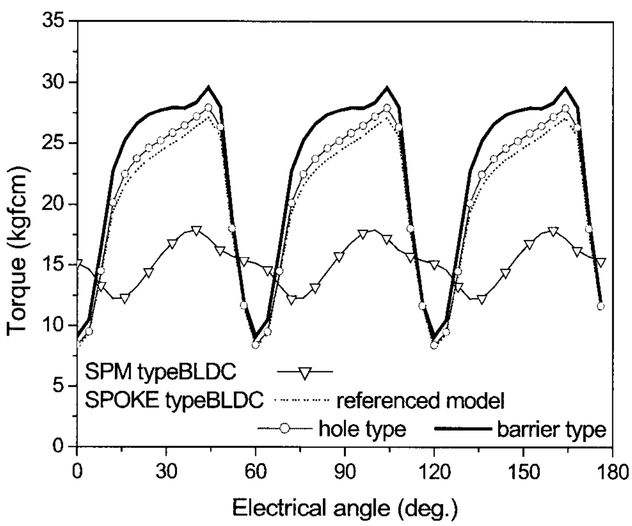


Fig. 15 Comparison of commutation torque.

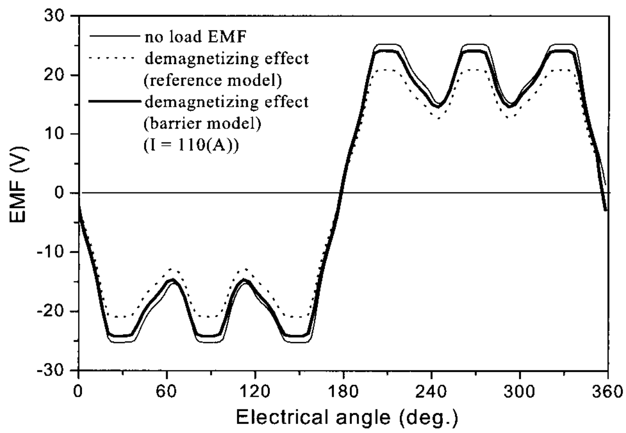


Fig. 16 Comparison of back EMF.

6. Conclusion

In this paper, the design of SPOKE type BLDC motor considering the irreversible demagnetization of PM has been performed for higher motor performance. So the irreversible demagnetization characteristics analysis is performed on three types of BLDC motors. From the analysis results, we confirmed that the SPOKE type BLDC motor has a great advantage over SPM and other IPM toward high torque and small size and the design process of the motor will have to consider the irreversible demagnetization characteristics.

Moreover, a new type of rotor shape has been proposed, which can concentrate the flux and as the results, flux barrier type rotor shape can maximize the torque, compared with the conventional types and also the durability of irreversible demagnetization phenomena are considerably increased by concentrated magnetic flux.

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